FM MULTIPLEX TUNER USING SILICON TRANSISTORS

By Larry Blaser

The transistor f-m tuner described in this paper is a high quality set comparable in performance to first line vacuum tube tuners under all reception conditions. It uses uhf and vhf silicon-planar transistors specifically designed for f-m and TV service. The tuner includes circuitry for receiving stereo f-m broadcasts but the basic tuner design is applicable to any vhf f-m receiver, either mobile or fixed. A block diagram of the tuner is shown in Fig. 1.

The tuner has been designed for the following characteristics: a rapid responding wide range agc, high sensitivity, high signal-to-noise ratio, good front-end rejection of unwanted signals, stability with temperature and voltage variations, flat-frequency response for multiplex reception, muting circuitry, and a multiplex demodulator and stereo indicator to form a complete stereo hi-fi component.

Results of performance tests, given in Table I, demonstrate that these criteria have been met or exceeded except for sensitivity. Additional investigation of the r-f and mixer stages is required to improve tuner sensitivity without sacrificing immunity to spurious responses.

FIG. 1 BLOCK DIAGRAM OF FM TUNER

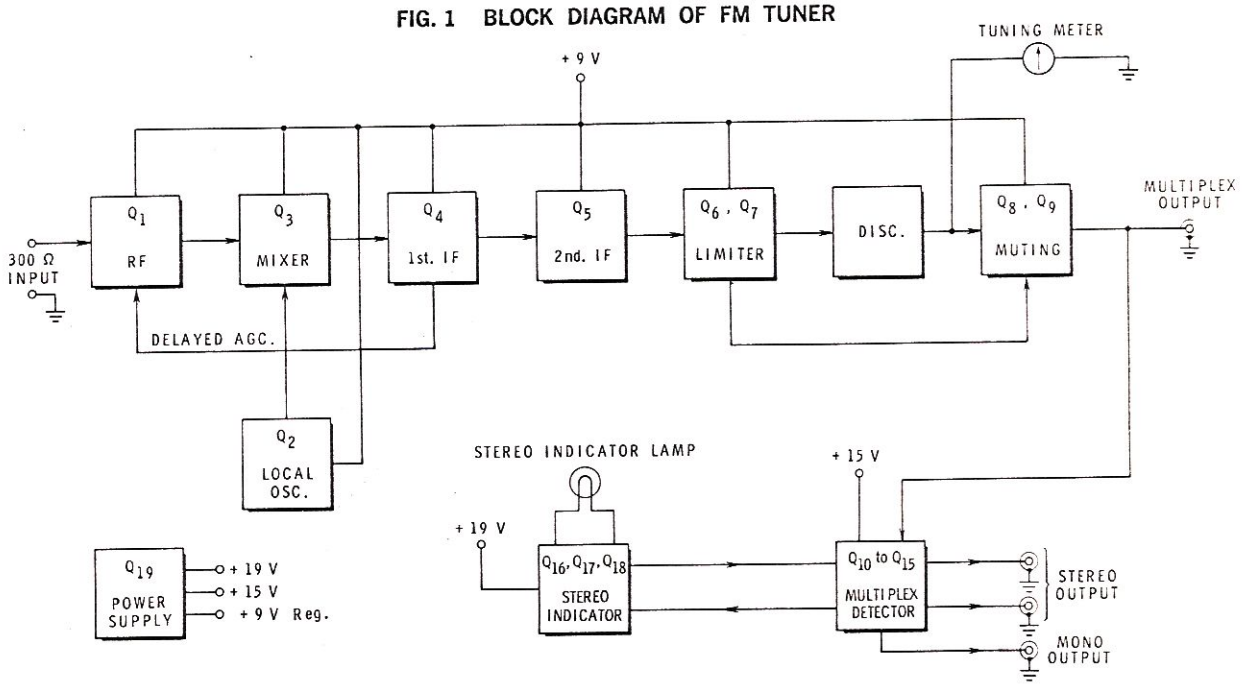

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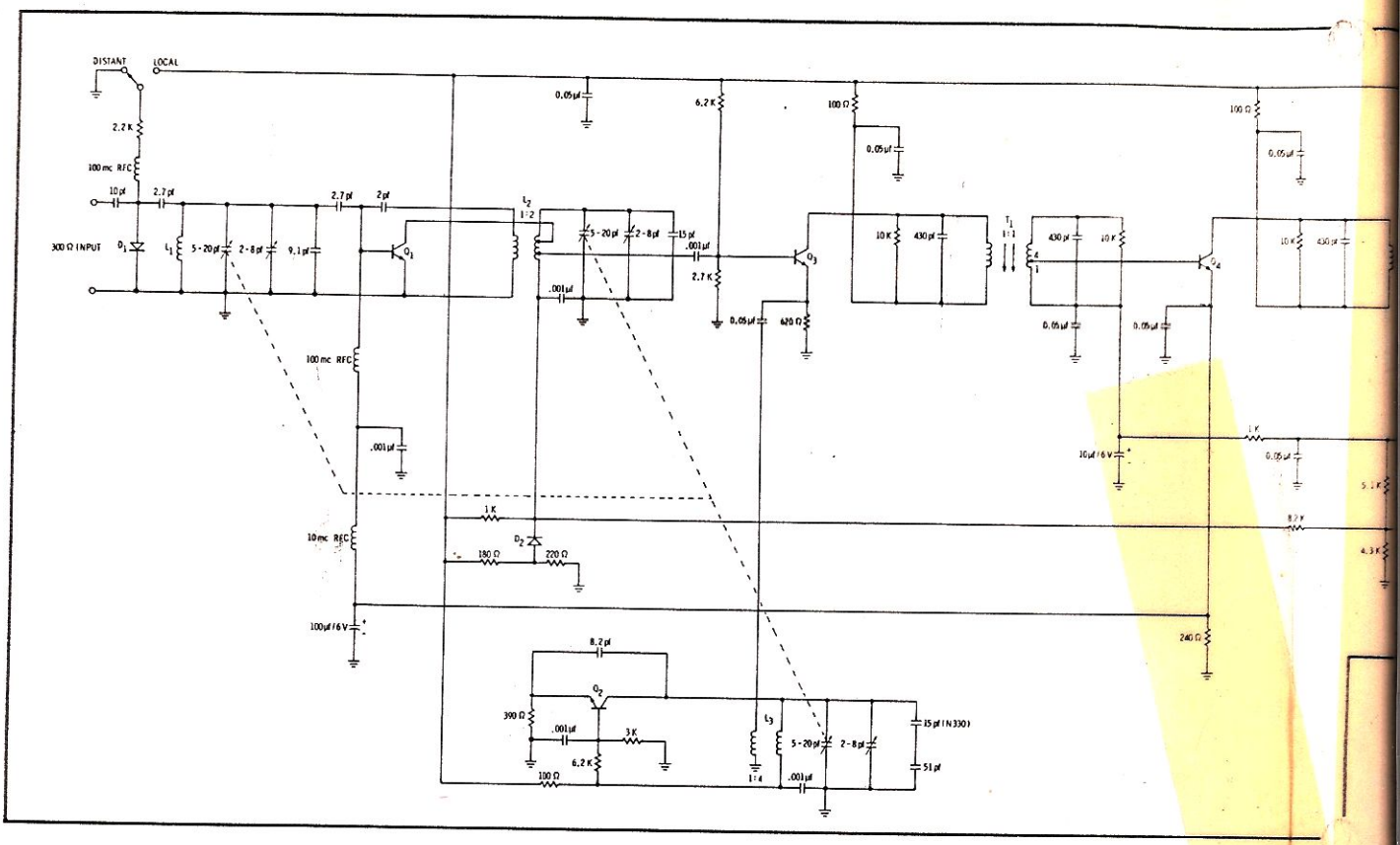
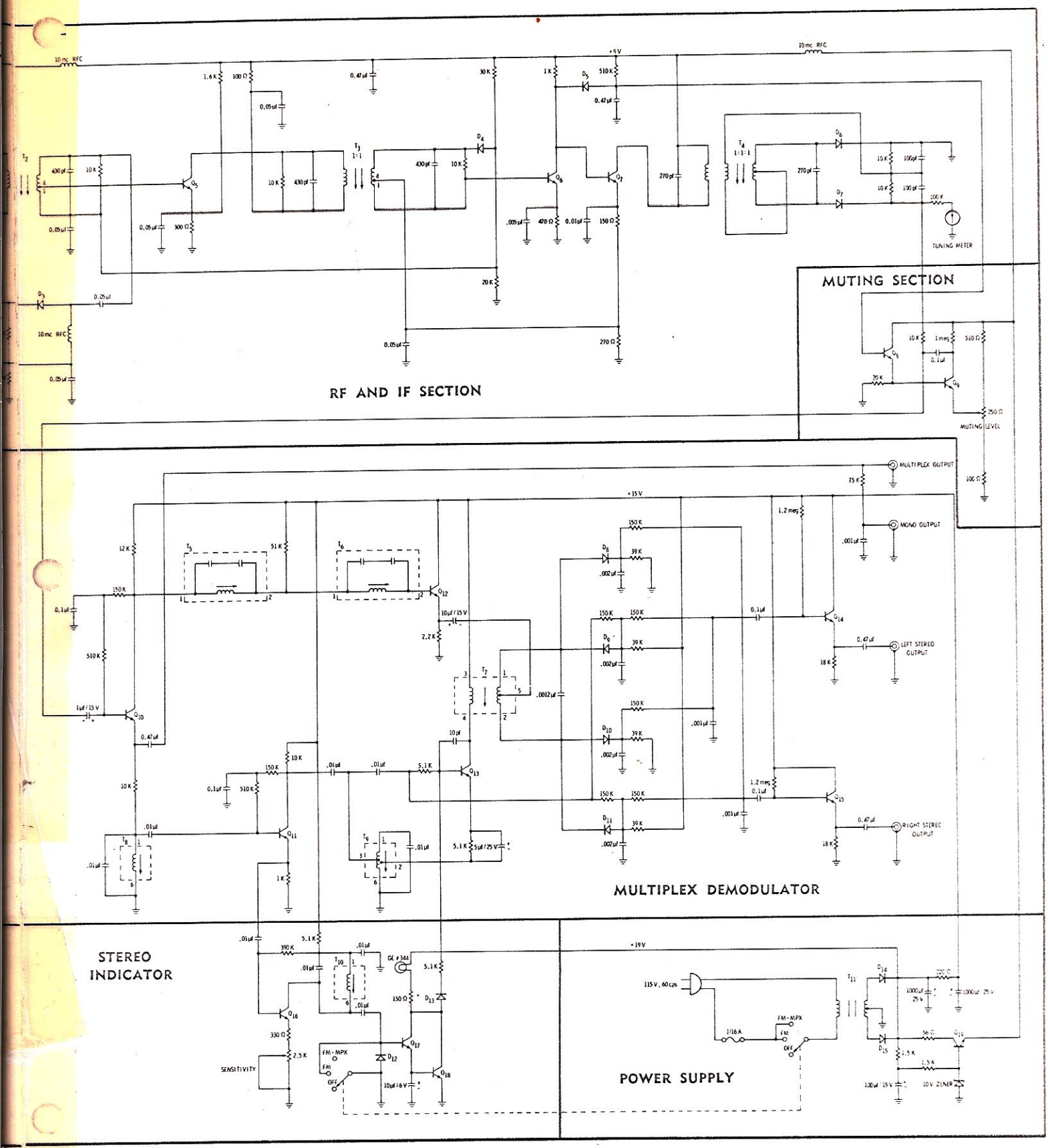
FIG. 2 SCHEMATIC DI



PARTS LIST

L_1	0.077 μh
L_2	0.077 μh, 4 turns tapped at 1 turn and 3 turns
L_3	0.056 μh
T_1, T_2, T_3	0.53 μh, $Q_{coil} = 80$
T_4	0.8 μh, $Q_{coil} = 80$
T_5, T_6	Miller No. 1352*
T_7	Miller No. 1355*
T_8, T_9, T_{10}	Miller No. 1354*
T_{11}	Triad No. F-40X*
D_1 to D_{13}	Fairchild entertainment type FD1335
D_{14}, D_{15}	FD200
Q_1	AGC transistor, Fairchild entertainment type SE-5001
Q_2 to Q_7	Fairchild entertainment type SE-3001
Q_8 to Q_{18}	Fairchild entertainment type SE-1001
Q_{19}	2N1613
*	Or equivalent

AGRAM OF FM MULTIPLEX TUNER



II CIRCUIT DESCRIPTION

Radio Frequency Amplifier

The r-f stage of an f-m tuner is the most critical design area. The noise figure must be low and available power gain should be high for good sensitivity, it should not produce spurious responses in the presence of high signals, the bandpass should not vary appreciably with agc, and the agc range should be sufficient to handle signals at the antenna of up to 1 volt.

The r-f stage is a neutralized common-emitter amplifier which uses a special uhf transistor designed for forward bias agc. This device gives good agc characteristics with less cross modulation than is possible with conventional devices[1, 2, 3]. The agc transistor, which is an experimental device at the time of this study, is similar to the 2N918 except that its high frequency h_{fe} falls off uniformly with increasing collector current without operating the device in heavy saturation. The 100 mc h_{fe} of this transistor with respect to collector current is shown in Fig. 3 with the 100 mc h_{fe} of the type 2N918 shown for comparison. Note that the peak current gain occurs at 2.5 mA which is the quiescent current of the design. At a collector current of 2.5 mA the device has a maximum available power gain at 100 mc of 28 db, and the 100 Mc noise figure with a 300-ohm source resistance is about 4 db.

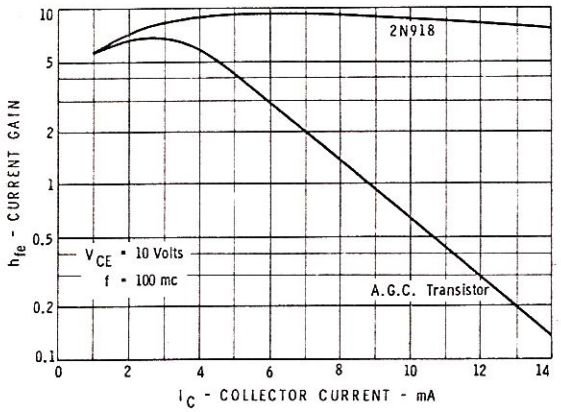


FIG. 3 100 mc h_{fe} Characteristic of AGC Transistor

The noise figure of the r-f stage is about 14 db* with a 300-ohm source resistance. This is higher than the noise figure of the transistor primarily because of the high insertion loss of the very narrow bandpass input filter (approx. 1 mc). The narrow filter, which is necessary for good front-end selectivity, therefore injects a compromise in design at the expense of optimum sensitivity.

Using the first i-f amplifier transistor, Q_4, as a delayed agc amplifier for the r-f stage, Q_1, more than 60 db gain reduction is provided in the r-f amplifier. A simplified circuit of the two stages contained in the agc network is shown in Fig. 4.

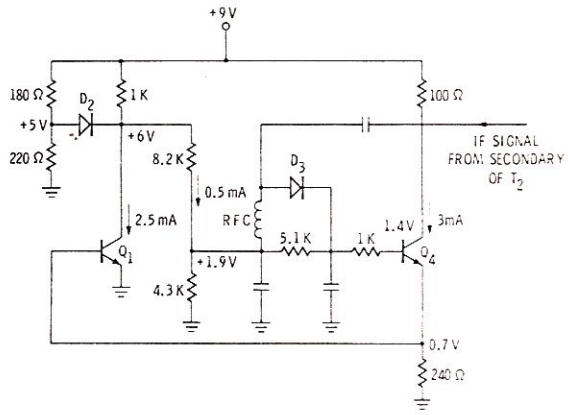


FIG. 4 Simplified Circuit of AGC Network

With no signal the collector voltage of Q_1 is 6 volts and the collector current is 2.5 mA. Diode D_2 is cut off as its anode is at 5.0 volts. Diode D_3 rectifies the signals at the 2nd i-f to produce a change in d-c bias voltage for input signal levels greater

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* Noise figure of the input stage is given by the equation:

$$NF = 10 \log \left[\frac{1}{K} \left(F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots \right) \right]$$

where R_s is the source resistance, R_d is the filter loss referred to the antenna input terminal and $K = R_d / (R_s + R_d)$. F_1 is the input transistor noise factor. F_2 is the mixer noise factor. G_1 is the available power gain ot the input transistor. G_2 is the available conversion gain of the mixer.

than 200 microvolts. This positive d-c voltage raises the bias on the base of Q_4 and the increased emitter current of Q_4 is passed back to the base of Q_1 raising its collector current and reducing the r-f gain. When the collector side of D_2 reaches about 4.3 volts, D_2 conducts, thus placing R_2 and R_3 in shunt with Q_1 holding the collector out of heavy saturation.

A local-distance switch is included in the r-f stage to provide 20 db reduction in gain before the input filter. When the switch is on diode D_1 conducts, shunting its resistance across the input. This feature is included as a precaution against the possibility of spurious responses in very high signal areas.

Mixer and Local Oscillator

The mixer and the local oscillator both use uhf transistors. The output of the r-f amplifier drives the base of the mixer and the local oscillator signal is injected into the emitter.

The local oscillator is very stable — the variation of oscillator frequency caused by r-f stage agc, supply voltage variations, and ambient temperature changes is well within the limits of the i-f bandwidth. This eliminates the necessity of afc which is often required in other f-m receivers. Low drift is primarily due to low capacitances of the transistor; and coupling to the emitter of the mixer rather than to the base eliminates frequency pulling with agc.

Intermediate Frequency Amplifier

The two stage unneutralized i-f amplifier has three identical, critically-coupled, 10.7 mc filters with 275 kc bandwidths at -3 db. The resulting flat top i-f response has a 240 kc bandwidth at -6 db which is adequate to pass the spectral components of a multiplex transmission yet is sufficiently narrow for good selectivity. Each stage has 25 db of stability limited gain with a stability factor of 4 with the first stage also acting as the delayed agc amplifier (see Appendix for the design of the i-f).

The second i-f amplifier has a 17 db range of agc which begins with input signals of about 50 microvolts. At about 200 microvolts the delayed agc of the r-f stage adds to the gain reduction, so that at an input of about 2 millivolts the amplified front-end agc contributes almost all the agc action. By delaying the agc of the front end, the signal-to-noise ratio at the discriminator output continues to improve as the input signal increases to about 2 millivolts. The over-all agc action is illustrated in Fig. 5.

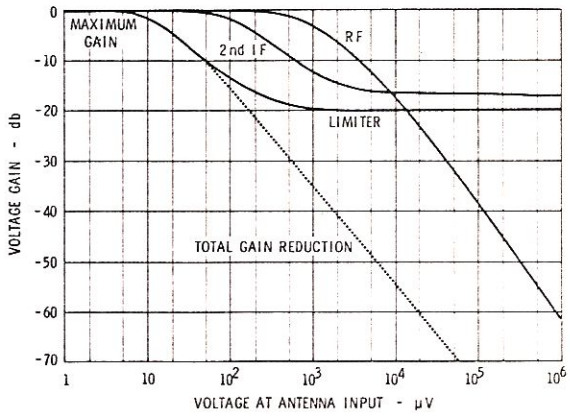

FIG. 5 Over-all AGC Action of Tuner

Limiter and Detector

A two transistor limiter stage discussed in Ref. 2 has a dynamic range of over 40 db with excellent a-m rejection throughout the audio range. The constant output characteristic of the limiter is provided by the feedback loop which also maintains stable d-c biasing.

The f-m detector is a conventional Foster-Seeley discriminator with circuit values chosen to pass the complete multiplex spectrum from 20 cps to 53 kc. The residual 10.7 mc i-f signal in the detector output is removed by a low-pass filter made up of a 10 kilohm resistor and the stray capacitances at the input of the multiplex demodulator. The tuning meter, which is connected to the detector, is included for ease of tuning consistent with other quality sets, but can be omitted with no affect on circuit operation.

Muting, Multiplex Demodulator, and Stereo Indicator Circuits

The two transistor muting circuit, which is activated by d-c bias developed in the limiter, bypasses the detector output to ground when the signal-to-noise ratio is low. Operation is as follows: Diode D_5 rectifies the signal from Q_6 of the limiter. With strong signals its anode voltage goes sufficiently negative to cut off Q_8 and Q_9. This allows the signal to pass through to the demodulator. Small signals or noise voltages are insufficient to turn on D_5, thus, Q_8 and Q_9 conduct and shunt the unwanted signals to ground through the 0.1 microfarad capacitor.

The multiplex demodulator is fully described in Ref. 4. The one deviation in its design is the inclusion of two emitter followers in the stereo outputs of the tuner so that the resulting low impedance output minimizes attenuation of high frequencies due to cable capacitance.

The 19 kc pilot, present as part of a stereo multiplex broadcast, is taken from the emitter of Q_{11} in the multiplex detector, amplified by Q_{16} and rectified by Q_{17} to operate an indicator lamp and to turn on the oscillator in the multiplex demodulator. When the tuner is receiving monophonic broadcasts the 19 kc pilot is not present in the received signal and the oscillator is turned off by saturation of Q_{13}. The two outputs from the multiplex detector are identical. By stopping the oscillator, the demodulator is made inoperative so that the signal-to-noise ratio of the tuner is not unnecessarily degraded by up to 23 db (Ref. 5) when receiving a monophonic broadcast.

Power Supply

The power supply has three outputs; a 19 volt output to operate the stereo indicator lamp, a low ripple 15 volt output for the multiplex demodulator and a series regulated 9 volts used for the tuner and muting circuits. The 9-volt supply was chosen for the tuner section as it is a convenient voltage obtainable from a series regulator in a 12-volt mobile electrical system. The stereo sections which operate from higher voltages would not be used in mobile applications.

Performance

The performance of the receiver is summarized in Table I.

III CONCLUSION

Performance of the tuner is comparable to quality vacuum tube tuners in most respects — oscillator stability is considerably better, while the sensitivity is not quite as good. Several methods of improving sensitivity without causing an increase in spurious responses are under investigation.

As this design is offered as a circuit study, the physical layout, shielding, coil fabrication and component selection of the r-f and i-f stages are not covered in this paper. These elements of design are left to the discretion of the manufacturer. To properly evaluate the requirements of shielding and layout for optimum performance, complete laboratory r-f equipment is usually necessary. Such work, therefore, should not be undertaken without proper facilities.

Acknowledgement: The author extends his thanks and recognition to Donald L. Smith for his careful work in the construction of the tuner.

TABLE I

PERFORMANCE SPECIFICATIONS

FM TUNER* - 88 MC TO 108 MC

IHFM SENSITIVITY
30 db Quieting . . . . . 7 μV

IHFM SIGNAL-TO-NOISE RATIO
. . . . . 62 db

TOTAL HARMONIC DISTORTION
1 kc . . . . . 0.4 %

OSCILLATOR PERFORMANCE AT 98 MC (except No. 4)

1. Warm-up drift after 1 minute . . 2 kc
2. Drift with ambient temperature referred to the oscillator frequency at 25°C:
   0° C . . . . . -17 kc
   50°C . . . . . -45 kc
   75°C . . . . . -109 kc
3. Oscillator shift for line voltage variations from 105 V to 125 V. . 1 kc
4. Oscillator shift referred to frequency at V_{CC}= 9V when voltage regulator is replaced with variable V_{CC} supply

Frequency	V_{CC}=8V	V_{CC}=10V
88 mc	-54 kc	+26 kc
98 mc	-32 kc	+ 5 kc
108 mc	-30 kc	+ 8 kc

5. Oscillator pulling with signal strength varied from IHFM sensitivity
   to 0.1 V. . . . . 0 kc
   to 1.0 V. . . . . 3 kc

FREQUENCY RESPONSE BEFORE DEEMPHASIS
1 db down . . . . . 7 cps and 45 kc
3 db down . . . . . <5 cps and 85 kc

IHFM CAPTURE RATIO
. . . . . 4 db

SELECTIVITY
100% modulated alternate channel. . . 30 db

SPURIOUS RESPONSES

Tuner set to 98 mc. Signal generator at 10.7 mc and through the band 50 mc to 480 mc (Responses more than 80 db not recorded)

10.7 mc (i-f).	47 db	119.4 mc(image).	60 db
96.5 mc . . .	79 db	336 mc	73 db
103.6 mc . . .	80 db	420 mc	73 db

INTERMODULATION DISTORTION
60 cps at ±60 kc deviation and 6 kc at ±15 kc deviation . . . . . 3.5 %

AUDIO HUM
Negligible

AM SUPPRESSION AT 98 MC
FM with 400 cps, 100% mod., AM with 1 kc, 30% mod.
10 db above IHFM sensitivity . . . 35 db
20 db above IHFM sensitivity . . . 39 db
40 db above IHFM sensitivity . . . 40 db

IHFM VOLUME SENSITIVITY
. . . . . 1.5 μV

* Measurement techniques, in general, are those outlined in "IHFM Standard Methods of Measurement for Tuners", Institute of High Fidelity Manufacturers, Inc. 125 E. 23rd St., New York 10, N. Y.

MULTIPLEX DEMODULATOR

1 KC HARMONIC DISTORTION (All measurements include noise, 19 kc, 38 kc, and harmonics thereof to 100 kc)

1. Monophonic input
   Left channel 0.75%
   Right channel 0.75%
2. Multiplex input (19 kc pilot on)
   Left channel, L=R=1 . . . . . 1.0%
   Right channel, L=R=1 . . . . 0.9%
   Left channel, L=1, R=0 . . . 1.5%
   Right channel, L=0, R=1 . . . 2.7%

SEPARATION (Undesired signal includes fundamentals and all harmonics and noise below 19 kc)

Frequency	Undesired Signal on Left	Undesired Signal on Right
50 cps	-28 db	-24 db
1 kc	-26 db	-26 db
5 kc	-20 db	-23 db
10 kc	-12 db	-12 db
15 kc	- 3 db	- 6 db

SIGNAL-TO-NOISE RATIO
Including 19 kc, 38 kc, and harmonics thereof to 100 kc . . . . . 40 db
Including only noise below 19 kc . . 61 db

APPENDIX

DESIGN OF EQUAL Q, DOUBLE-TUNED, CRITICALLY-COUPLED I-F FILTERS[6]

A. Design Procedure*

1. Determine the "y" parameters of the transistor at the center frequency of the i-f.
2. Find the maximum available gain of the transistor.

$$MAG = \frac{|y_f|^2}{4\, g_i\, g_o}$$

3. Find the stability limited gain of a stage.

$$SLG = \frac{|y_f|}{S|y_r|q^2}$$

where S, the stability factor, is the reciprocal of the loop gain at the frequency where the loop gain is real. The factor q, which is obtained from Fig. 1-A, is the ratio of the total admittance across the transistor input at resonance to the admittance at the frequency at which the loop gain is real.

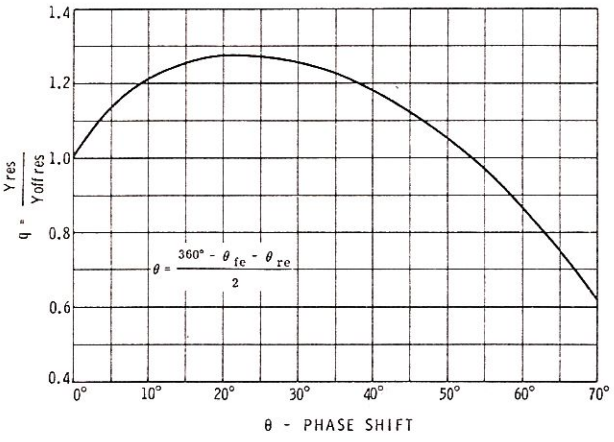

FIG. 1A Factor q vs phase shift.

4. Find the insertion loss required in the filter.

IL (db) = MAG (db) - SLG (db)

5. Determine the required loaded Q, Q_L, of the filter coils.

$$Q_L = \frac{f\sqrt{2}}{B}$$

where f is the center frequency of the i-f and B is the required 3 db bandwidth of each stage.

6. Determine the required unloaded Q, Q_o, of the filter coils from the equation:

$$IL\ (db) = 20 \log \frac{Q_o}{Q_o - Q_L}$$

7. Using the configuration shown in Fig. 2-A, determine the total tuning capacitances, the coil inductances and the turns ratio of the secondary coil.

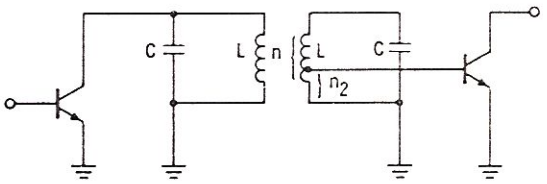

FIG. 2A Simplified i-f amplifier stage.

$$C = \frac{g_o}{2\pi f} \cdot \frac{Q_o Q_L}{(Q_o - Q_L)}$$

$$L = \frac{1}{2\pi^2 f^2 C}$$

$$\frac{n}{n_2} = \sqrt{\frac{g_i}{g_o}}$$

B. Design of the 10.7 mc Filters

1. The common-emitter "y" parameters of the uhf transistor used in the i-f are given in Table I-A for the bias conditions of the

* This is a simplified procedure from which approximate but in general adequate designs can be obtained. For more exact analyses of i-f amplifiers, refer to reference 6, and the bibliography.

TABLE I-A

COMMOM EMITTER "y" PARAMETERS OF I-F TRANSISTORS

CONDITIONS: V_{CE} = 7 V I_C = 3 mA f = 10 mc			
INPUT ADMITTANCE	OUTPUT ADMITTANCE	FORWARD TRANSCONDUCTANCE	REVERSE TRANSCONDUCTANCE
g_{ie} = 1.5 mmhos	g_{oe} = 0.065 mmhos	g_{fe} = 85 mmhos	g_{re} = -0.01 mmhos
b_{ie} = 0.6 mmhos	b_{oe} = 0.135 mmhos	b_{fe} = -30 mmhos	b_{re} = -0.08 mmhos
		$\|y_{fe}\|$ = 90 mmhos	$\|y_{re}\|$ = 0.08 mmhos
		θ_{fe} = -19.5°	θ_{re} = 263°

devices in the circuit; V_{CE} = 7 V and I_C = 3 mA.

2. The maximum available gain at these conditions is

   MAG = 20800 (43.2 db)

3. Referring to Fig. 1-A,

$$\theta = \frac{360° - \theta_{fe} - \theta_{re}}{2} = 58.3°,$$

therefore

$$q = 0.9$$

Using a stability factor of 4, the stability limited gain is

SLG = 347 (25.4 db)

4. The insertion loss required in the filter therefore is

   IL = 17.8 db

5. The loaded Q of the coils in the filter is

$$Q_L = 55$$

6. From the equations

$$IL = 20 \log \frac{Q_o}{Q_o - Q_L}$$

and

$$Q_L = \frac{f\sqrt{2}}{B}$$

the required coil Q is

$$Q_o = 63$$

7. The total required tuning capacitance is

$$C_T = 420 \text{ pf}$$

The contribution of the transistor to the total capacitance is small so

$$C \simeq C_T = 420 \text{ pf} \simeq 430 \text{ pf}$$

The required inductance of the coils is

$$L = 0.525 \ \mu h$$

and the turns ratio of the secondary coil (Fig. 2-A) of the transformer is

$$\frac{n}{n_2} = 4.8 \simeq 5$$

The 0.525 μh coils wound for this filter have a Q of 81. To obtain the desired value of Q_o = 63, each coil is damped with a resistance

$$R_d = \frac{2\pi fL}{\left(\frac{1}{Q_o} - \frac{1}{Q_c}\right)} = 9.8 K\Omega \simeq 10 K\Omega$$

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